

Evidence for millimeter-wave coherent emission from the NSLS VUV ring

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Abstract

Coherent synchrotron radiation from the NSLS VUV ring has been detected and partially characterized. The observations have been performed at the new far infrared beamline U12IR. The coherent radiation is peaked near a wavelength of 7mm and occurs in short duration bursts. The bursts occur only when the electron beam current (I) exceeds a threshold value (I_{th}), which itself varies with ring operating conditions. Beyond threshold, the average intensity of the emission is found to increase as $(I - I_{th})^2$. The coherent emission implies micro-bunching of the electron beam due to a longitudinal instability.

Keywords: coherent synchrotron radiation, longitudinal beam instability, millimeter waves.

INTRODUCTION

Synchrotron radiation is produced when light, charged particles (typically electrons) traverse the magnetic guide structure of an accelerator or storage ring. The electrons normally travel in "bunches" with each bunch containing a large number of particles. The radiation intensity produced by multiple particles emitting synchrotron radiation can be written as^{1,2}

$$\frac{dI}{d\omega}_{multiparticle} = [N + N(N-1)f(\omega)] \frac{dI}{d\omega}_{one\ particle} \quad (1)$$

where N is the number of particles,

$$\frac{dI}{d\omega}_{one\ particle} = \int \frac{e^2 \omega^2}{4\pi^2 c} \left| \int_{-\infty}^{\infty} \hat{n} \times (\hat{n} \times \vec{\beta}) e^{i\omega[t - \hat{n} \cdot \vec{r}/c]} dt \right|^2 d\Omega \quad (2)$$

is the spectral dependence of the synchrotron radiation emitted by a single particle, and

$$f(\omega) = \left| \int_{-\infty}^{\infty} e^{i\omega \hat{n} \cdot \vec{r}/c} S(r) dr \right|^2 \quad (3)$$

is the Fourier transform of the (normalized) longitudinal electron density $S(r)$. For spectral ranges where $f(\omega)$ is effectively zero, eq. 1 gives an intensity that scales linearly with the number of particles. This is

standard incoherent synchrotron radiation emission. But for spectral ranges where $f(\omega)$ is not zero, $dI/d\omega$ has a *coherent* term that scales as N^2 for large N . Since N is typically very large ($\sim 10^{10}$ particles), the coherent part easily dominates over the incoherent term. For a typical electron bunch with Gaussian longitudinal density function, the spectral range for coherent emission is also Gaussian with width $\sigma_\omega = c/2\pi\sigma_L$ where σ_L is the bunch length. A 10 cm electron bunch (300 ps duration) therefore emits coherently for frequencies up to ~ 1 GHz. Such emission is normally not observed³ as the waveguide cutoff frequency for the storage ring's metallic vacuum chamber is typically around 10 GHz. But if the electron bunch is short enough (i.e., ≤ 10 ps duration), or a short period modulation of the bunch density can be imposed, coherent emission at observable frequencies can occur. From eq. 1., the ratio of the coherent to incoherent radiated intensity is

$$\frac{P(\omega)_{coherent}}{P(\omega)_{incoherent}} \cong Nf(\omega) \quad (4)$$

so that a measure of this ratio can be used to extract information on the longitudinal particle density function using eq. 3 (the precise density can not be determined without phase information). This has been previously observed and utilized in linac-driven systems^{4,5}.

EXPERIMENT

Our measurements were conducted using the VUV ring at the National Synchrotron Light Source (NSLS/Brookhaven National Laboratory). This storage ring has a low emittance, double-bend achromat lattice (bending radius = 1.91 m) and serves as a dedicated synchrotron radiation source. The rf accelerating system operates at 52.88 MHz and the ring orbit frequency is 5.88 MHz. Though the ring energy can be varied from below 500 MeV to 800 MeV, we conducted most of our studies at the injection energy of 737 MeV and with a single bunch of circulating electrons (to avoid coupled-bunch effects).

Emission of far infrared and millimeter radiation is detected at U12IR, one of 6 infrared beamlines at the NSLS built on bending magnet ports. The U12IR beamline extracts 90 mr by 90 mr of radiation through a 6 cm square aperture in the storage ring dipole chamber. From here, the infrared radiation is transported by mirror optics to the entrance of 12.7 mm diameter cylindrical metal waveguide known as "light pipe". A light cone assists in coupling the radiation into the pipe. The light pipe then transports the radiation to a lamellar grating interferometer and ^4He cooled bolometric detector. The interferometer functions as a standard Fourier transform infrared (FTIR) spectrometer except that interference occurs between light reflected from the front and back surfaces of a faceted mirror (the lamellar grating). Such instruments attain very high modulation efficiency in the very far infrared (below 50 cm^{-1} or wavelengths longer than 0.2 mm). The longest detectable wavelength for this system is ~ 20 mm, due to the cutoff effects of the 12.7mm diameter light pipe. The detector response has a fall time between 200 and 800 μs . The rise time is not well known, but is substantially shorter (a few microseconds). A schematic of the beamline and spectrometer is shown in Figure 1 and a photograph of the lamellar grating is shown in Figure 2. More complete details of the beamline's performance are published elsewhere⁶.

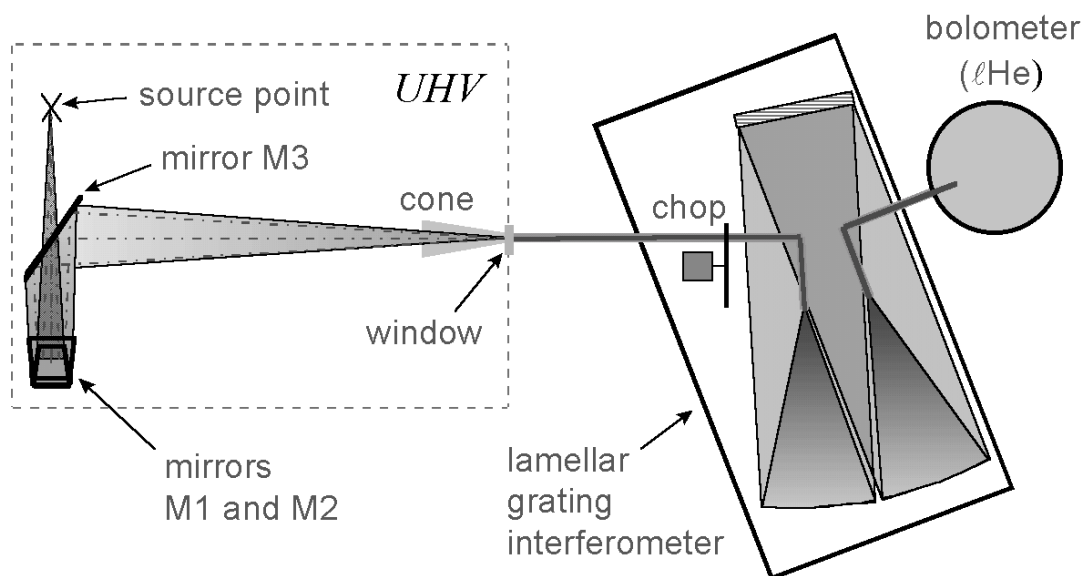


Figure 1. Schematic of the optical path for the U12IR far infrared beamline at the NSLS.

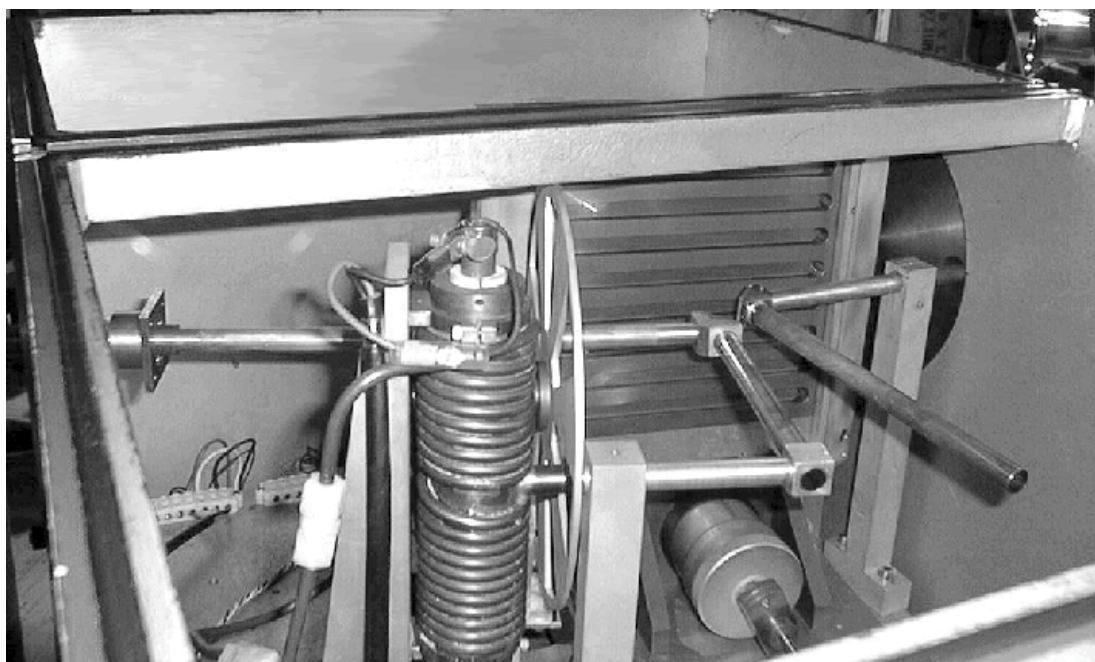


Figure 2. Photograph showing the interior workings of the FTIR spectrometer. The lamellar grating is visible on the right, toward the rear. The lightpipe for transporting the infrared is clearly visible, along with the micrometer drive for moving the grating. The cylindrical object with coiled tubing houses a mercury arc lamp which serves as an alternative infrared source for alignment and calibration.

On the time scale over which the infrared detector averages (microseconds or longer), and for normal operations of the VUV ring (i.e. 800MeV, stretched bunches), the far IR power is temporally smooth and varies linearly with beam current as expected for incoherent synchrotron radiation. But for other operating conditions, bursts of radiation are observed at the detector when the beam current exceeds a threshold value (which depends on the ring's operating parameters). An example of these bursts is shown in Figure 3. Typically, bursts occur with varying amplitude, and at time intervals ranging from ~ 1 ms to ~ 10 ms. The growth rate of these particular bursts is faster than the resolution of our detector (a few microseconds). The

decay time is also detector limited at $\sim 200 \mu\text{s}$. As the current is increased beyond the threshold value, the magnitude of a typical burst increases. This occurs in a manner such that the time-average power increases as the square of the excess beam current (i.e., current over threshold), as shown in Figure 4.

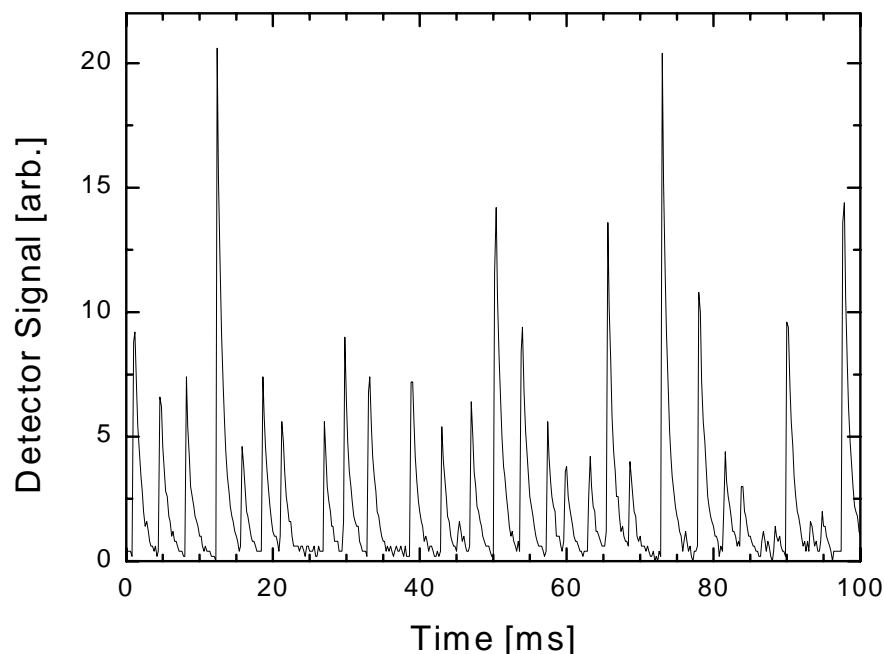


Figure 3. Far infrared detector output versus time showing emission bursts under conditions of coherent emission.

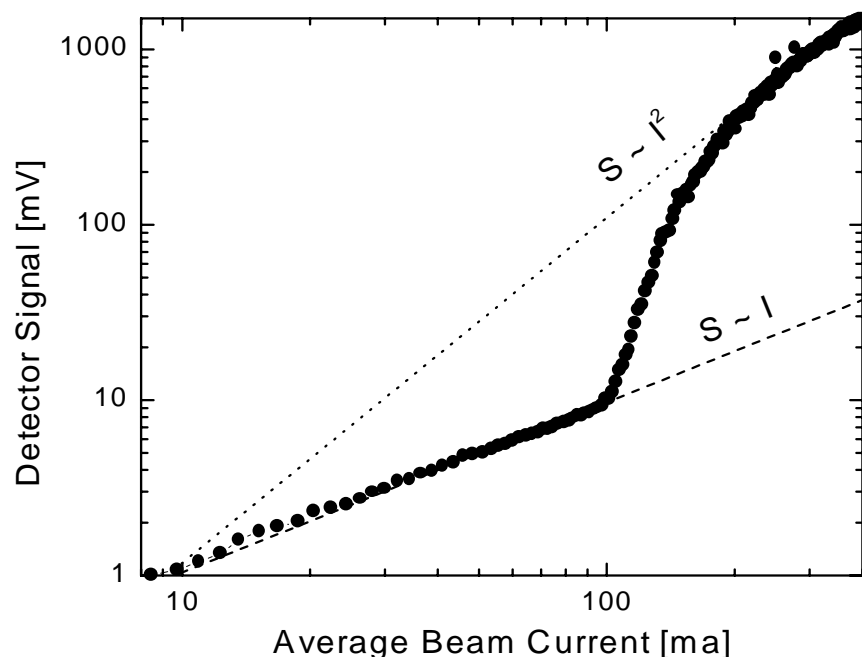


Figure 4. Measured output power versus average beam current in a single bunch, showing the onset of coherent emission at $I_{th} = 100 \text{ ma}$.

Spectra for both coherent and normal (incoherent) emission were recorded and ratioed, thus eliminating characteristics associated with the instrument's own response as well as the intrinsic spectral content of normal (incoherent) synchrotron radiation emission. The spectra take several minutes to acquire, and thus

represents the time-averaged signal over many coherent bursts. The result is a peak close to 7 mm wavelength (42 GHz) (see Figure 5). The data quality is not sufficient to extract a precise line shape for the emission feature, but the extended "wings" (visible to nearly 3 cm^{-1}) are inconsistent with either a Gaussian or Lorentzian shape. Since the lower frequency limit of the lightpipe and spectrometer is $\sim 0.5 \text{ cm}^{-1}$ ($\lambda = 20 \text{ mm}$), the existence of emission features at lower frequencies can not be ruled out.

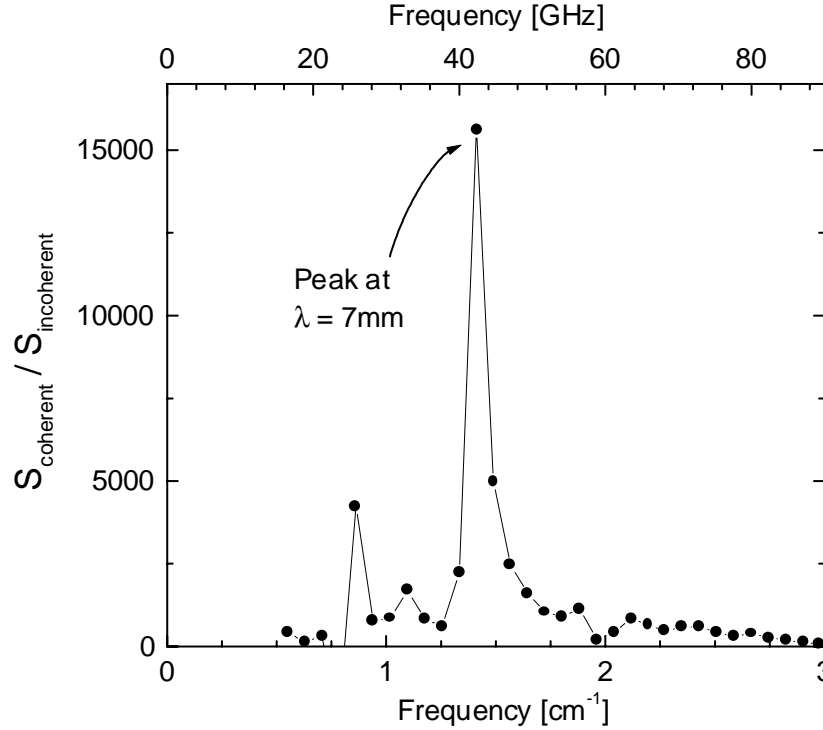


Figure 5. Power spectral content of the coherent emission, relative to the incoherent synchrotron spectrum. The measured signal is the time-average over many emission bursts.

DISCUSSION

The spectral content of the coherent emission can be used to extract an estimate for the longitudinal density modulation during an instant of time when the instability is present. In addition to the experimentally determined spectral content shown in Figure 5., a non-detectable Gaussian content at lower frequencies is assumed (see Fig. 6) to account for the known overall shape of an electron bunch. The Gaussian amplitude was chosen to be a factor of 100 greater than the 7 mm wavelength emission peak. A real Fourier transform results in the density function shown in Fig. 7. The actual magnitude of the 7 mm feature is not known, and in fact varies with time as the instability develops and subsides. Even at a peak of the instability, the magnitude is not well-known since our detector is unable to resolve it temporally. We therefore make a rough estimate based on the relative magnitudes of the average coherent and incoherent emission signals (enhancement factor of $\sim 10^4$) and the peak versus average signal assuming a 0.01% duty cycle (an additional factor of $\sim 10^4$). Since there are approximately 10^{11} electrons in a bunch, a full (100%) density modulation would lead to an enhancement factor of 10^{11} . Our estimated actual enhancement factor is then $\sim 10^8$, corresponding to a $\sim 0.1\%$ density modulation – a factor of 10 smaller than that shown in Fig. 7. Since we do not have phase information, that the density modulation is centered on the Gaussian bunch peak is an assumption.

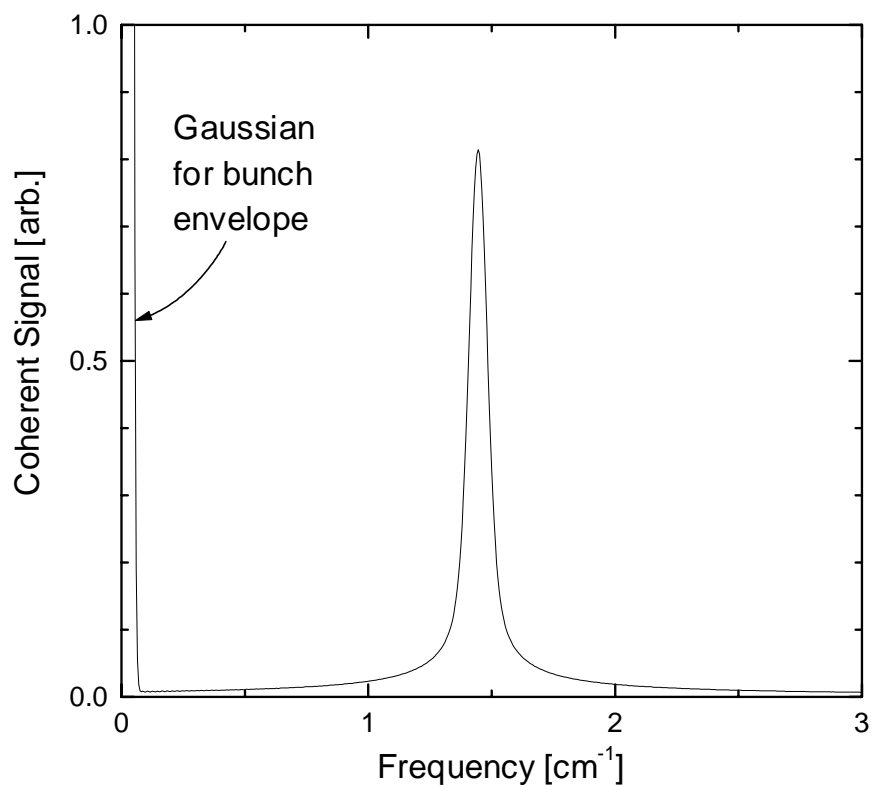


Figure 6. Modeled shape of the coherent emission's spectral content.

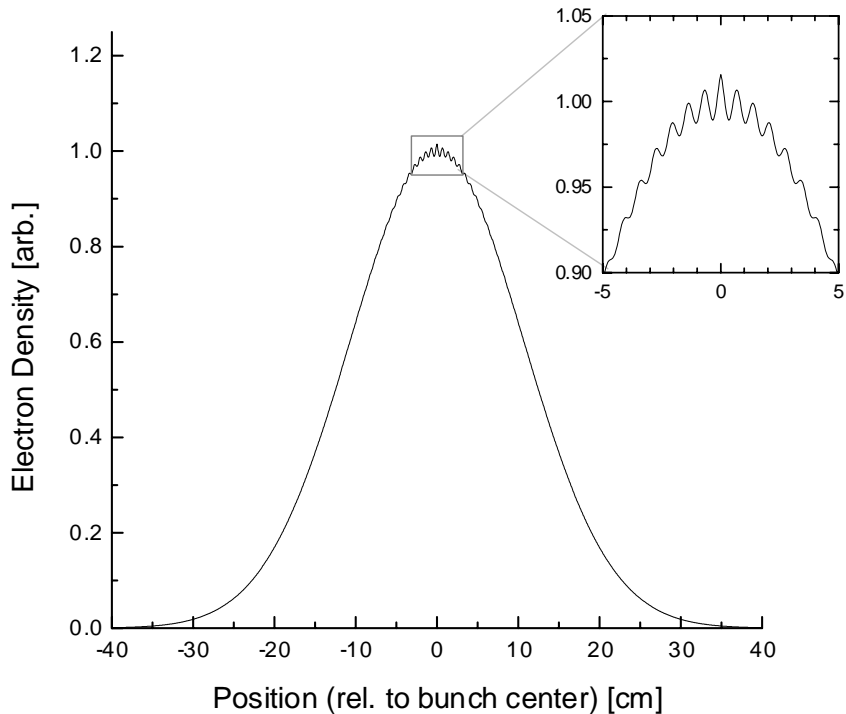


Figure 7. Fourier transform of the coherent spectral content shown in Fig. 6., resulting in an estimated longitudinal electron bunch density at a moment when a large burst of coherent emission is observed. The modulation is assumed centered on the bunch.

The wavelength of the emission bursts and the unusual time-structure suggest a process related to the so-called microwave instability⁷. This particular type of longitudinal instability can result when electrons interact with each other through a short range wakefield. The wakefield can be characterized by a complex impedance determined by the beam pipe, rf cavities, and other structures that make up the electron vacuum chamber such as beam ports and bellows.

As noted above, the rate at which the instability grows and decays is typically faster than our detector can resolve. While the decay rate was never resolved, we know that it must be faster than $\sim 200 \mu\text{s}$, which is more than an order of magnitude shorter than the synchrotron damping time ($\sim 10 \text{ ms}$). Thus, the decay is not attributed to synchrotron radiation damping. At present we do not understand what determines the time structure of the bursts.

Burst of coherent synchrotron radiation in the 10 to 20 GHz spectral range have also been reported⁸ at SURF II (NIST). While the temporal behavior shows similarities, the spectral content is very much different and no threshold current was reported.

SUMMARY

The NSLS VUV ring produces coherent emission with a wavelength of 7 mm. The emission appears in short ($< 200 \mu\text{s}$ duration) bursts and at intervals of a few milliseconds. The emission bursts occur only when the beam current exceeds a threshold value that varies with the operating conditions of the synchrotron. We attribute the coherent emission to a longitudinal density modulation that results from a beam instability, possibly related to the microwave instability. The particular properties of the storage ring leading to the density modulation are as yet unknown.

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